

# Resonant spin transport through a superconducting double barrier structure

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PACS 73.23.-b – Electronic transport in mesoscopic systems

PACS 74.45.+c – Proximity effects; Andreev effect; SN and SNS junctions

PACS 72.25.Ba – Spin polarized transport in metals

**Abstract.** – We study resonant transport through a superconducting double barrier structure. At each barrier, due to the proximity effect, an incident electron can either reflect as an electron or a hole (Andreev reflection). Similarly, transport across the barrier can occur via direct tunneling as electrons as well as via the crossed Andreev channel, where a hole is transmitted. In the subgap regime, for a symmetric double barrier system (with low transparency for each barrier), we find a new  $T = 1/4$  resonance ( $T$  is the transmission probability for electrons incident on the double barrier structure) due to interference between electron and hole wave-functions between the two barriers, in contrast to a normal double barrier system which has the standard transmission resonance at  $T = 1$ . We also point out as an application that the resonant value of  $T = 1/4$  can produce pure spin current through the superconducting double barrier structure.

**Introduction.** – Effects due to the proximity of a superconductor have motivated a lot of research in the recent past both from theoretical [1–10] as well as experimental [11, 12] point of view. Due to the proximity effect, an electron incident on a normal metal-superconductor (NS) interface reflects back as a hole and as a consequence, two electrons are transferred into the superconductor as a Cooper pair. This phenomenon is known as Andreev reflection (AR) [13] in the literature of mesoscopic superconductivity. An even more intriguing example where the proximity effect manifests itself is the phenomenon of crossed Andreev reflection (CAR) [7–9, 14] in which an electron from one of the normal leads of a normal metal-superconductor-normal metal (NSN) junction pairs up with another electron from the other lead and as a result, a Cooper pair jumps into the superconductor. This nonlocal process can only take place if the separation between the points of coupling of the two normal metal leads with the superconductor is of the order of the size of the Cooper pair itself. From the application point of view, the relevance of CAR in the manipulation of pure spin currents (SC) [15], spin filter [16] and production of entangled electron pairs in nanodevices [17–19] has attracted a lot of interest in recent times.

Motivated by these facts, in this letter, we adopt the simple-minded definition of SC which is commonly used

in literature [20–22]. It is just the product of the local spin polarization density associated with the electron or hole, (a scalar  $s$  which is either positive for spin-up or negative for spin-down) and its velocity. To generate a pure SC in the sense defined above, one can have the two most obvious scenarios where (a) there exists an equal and opposite flow of oppositely spin-polarized electrons through a channel, such that the net charge current through the channel is nullified leaving behind a pure SC, or (b) alternatively, there exists an equal flow of identically spin polarized electrons and holes in the same direction through a channel giving rise to pure SC with perfect cancellation of the charge current. In this letter, we explore the second possibility for generating resonant pure SC using a superconducting double barrier (SDB) structure.

## Proposed device and its theoretical modelling.

– The configuration we have in mind for the generation of resonant pure SC is shown in Fig.1. The idea is to design a SDB structure by depositing thin strips of superconducting material on top of a single channel, ballistic, one-dimensional (1-D) lead at two places, which can induce a finite superconducting gap ( $\Delta_i e^{i\phi_i}$ ) in the barrier regions as a result of proximity effect of the superconducting strips. If the width of the strips is of the order of the phase coherence length of the superconductor, then

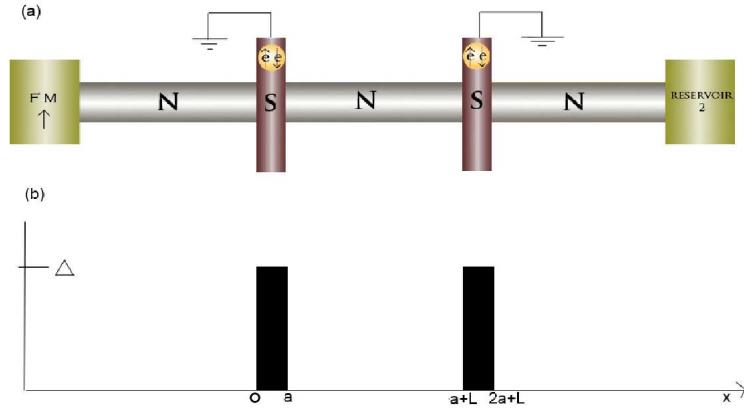


Fig. 1: (a) Cartoon of the SDB structure where a single channel, ballistic, 1-D normal metal (N) lead is connected to a ferromagnetic (F) reservoir at its left end and to a normal reservoir at its right. Two patches at the two places on the lead depict superconducting material deposited on top of it. (b) Schematic of the potential profile seen by an incident electron.

both direct electron to electron co-tunneling (CT) as well as crossed-Andreev electron to hole tunneling can occur across the SDB region. Here it is worth mentioning that we restrict ourselves to spin singlet superconductors so that both elastic CT and CAR across the junction conserve spin. In our theoretical modeling of the system (see Fig. 1), we first assume that the S-matrix representing the SDB structure described above respects parity (left-right symmetry) and spin-rotation symmetry, so that we can describe the system by an S-matrix with only eight independent parameters namely, (i) the normal reflection amplitude ( $r_c$  ( $\tilde{r}_c$ )) for e (h), (ii) the transmission or CT amplitude ( $t_c$  ( $\tilde{t}_c$ )) for e (h), (iii) the Andreev reflection (AR) amplitude ( $r_{Ac}$  ( $\tilde{r}_{Ac}$ )) for e (h), and (iv) the crossed Andreev reflection (CAR) amplitude ( $t_{Ac}$  ( $\tilde{t}_{Ac}$ )) for e (h). (We have used the subscript  $c$  to denote the composite amplitudes for the SDB structure and tilde to distinguish the amplitudes for incident holes from the incident electron). If we inject spin polarized electron ( $\uparrow$  e) from the left lead using a ferromagnetic reservoir and tune the system parameters such that  $t_c$  and  $t_{Ac}$  are equal to each other, it will lead to a pure SC flowing to the right lead. This is so because, on an average, an equal number of electrons ( $\uparrow$  e) (direct electron to electron CT) and holes ( $\uparrow$  h) (CAR of electron to hole tunnelling) are injected from the left lead to the right lead resulting in the cancellation of the average charge current, whereas the spins add, giving rise to pure SC in the right lead. Note that spin up holes ( $\uparrow$  h) implies a Fermi sea with an absence of spin down electron (which is needed for the incident electron ( $\uparrow$  e) to form a Cooper pair and jump into the singlet superconductor).

**Superconducting double barrier.** – Quantum transport in the SDB structure has been studied earlier by Morpurgo *et al.* in Ref. [6]. In their work, they assumed that both the barriers were reflectionless and also that there was no CAR across either of the barriers. They

then obtained the resultant Andreev reflection and transmission amplitudes across the SDB by considering multiple AR processes between the barriers and found a  $T = 1$  resonance. In this letter, we address the full problem allowing all the quantum mechanical processes occurring across the two barriers. Hence our set-up is very similar to that given in Ref. [6], and comprises of a ballistic normal 1-D lead with two short, but finite superconducting patches deposited on top of it as shown in Fig.1. Here the structure is connected to ideal ferromagnetic and normal electron reservoirs respectively at its two ends.  $\Delta_i$  and  $\phi_i$  are the pair potentials and order parameter phases on the two patches respectively ( $i$  refers to the index of the strips). The space dependence of the order parameter (which also acts as a scattering potential) for the incident electron can be expressed as

$$\Delta(x) = \Delta^{(i)} e^{i\phi_1} \Theta(x) \Theta(-x + a) + \Delta^{(i)} e^{i\phi_2} \Theta[x - (a + L)] \Theta[-x + (2a + L)] \quad (1)$$

where,  $a$  is the width of the SB,  $L$  is the distance between the two barriers and  $\Theta$  is the Heaviside  $\Theta$  function.

In contrast to Ref. [6], to obtain the resultant reflection, transmission, AR and CAR for the SDB structure, one needs to consider all the multiple reflection processes in the SDB due to both  $r_i$  and  $r_{Ai}$  for each of the barriers labelled by  $i$ . So an electron which enters the region between the two barriers has a choice of being reflected as an electron or being converted to a hole at each bounce. For the numerical analysis, it is more convenient to use the alternate method to solve such scattering problems, which is to use the standard wave-function matching technique.

The one-dimensional Bogolubov–de Gennes (BdG) equation [23] for (spin up and spin down) electrons and

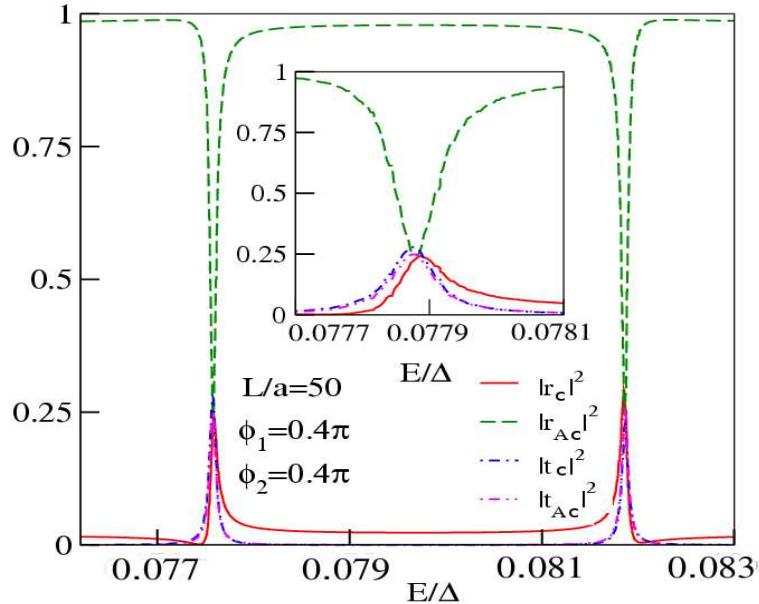


Fig. 2: The variation of  $|r_c|^2$ ,  $|t_c|^2$ ,  $|r_{Ac}|^2$  and  $|t_{Ac}|^2$  is plotted in units of  $e^2/h$  as a function of  $E/\Delta$  for a symmetric SDB system.  $\Delta/E_F$  has been chosen to be 0.275. Inset: The region close to one of the resonances is expanded in the inset. Note the existence of two closely spaced resonances.

holes can be written as

$$Eu_+ = \left[ \frac{-\hbar^2 \nabla^2}{2m} + V(x) - \mu_L \right] u_+ + \Delta u_- \quad (2)$$

$$Eu_- = \left[ \frac{\hbar^2 \nabla^2}{2m} - V(x) + \mu_R \right] u_- + \Delta^* u_+ \quad (3)$$

The solution of the BdG equations, describing electrons and holes with incident energy  $E$  inside the normal regions ( $\Delta_{(i)} = 0$ ), can be written as

$$\Psi_e^{\pm q^+ x}(x) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{\pm i q^+ x} \quad (4)$$

$$\Psi_h^{\mp q^- x}(x) = \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{\mp i q^- x} \quad (5)$$

where,  $\hbar q^\pm = \sqrt{2m(E_F \pm E)}$  and the  $\pm$  sign in the exponent of the plane wave solutions corresponds to an excitation propagating in the  $\pm x$  direction.

Similarly, inside the superconducting barrier regions the solutions for electronlike and holelike excitations are

$$\Psi_e^{\pm k_i^+ x}(x) = \begin{pmatrix} u_{i+} e^{\pm i \phi_i} \\ u_{i-} \end{pmatrix} e^{\pm i k_i^+ x} \quad (6)$$

$$\Psi_h^{\mp k_i^- x}(x) = \begin{pmatrix} u_{i-} e^{\pm i \phi_i} \\ u_{i+} \end{pmatrix} e^{\mp i k_i^- x} \quad (7)$$

where,  $\hbar k_i^\pm = \sqrt{2m(E_F \pm (E^2 - \Delta_{(i)}^2)^{1/2})}$ ,  $u_\pm = \frac{1}{\sqrt{2}}[(1 \pm (1 - (\Delta_{(i)}/E)^2)^{1/2})]^{1/2}$ ,  $m$  is the effective mass of the electron and  $E_F$  is the Fermi energy of the system.

Hence matching the wavefunctions for the normal and superconducting regions (Eq.(4-7)) at the four NS interfaces ( $x = 0, a, a + L, 2a + L$ ) forming the SDB structure, we obtain sixteen linear equations. Numerically solving these sixteen equations we obtain the  $4 \times 4$  S-matrix for the SDB structure which, for an incident electron with energy  $E$ , can be written as

$$S_e = \begin{bmatrix} r_c & t_c & r_{Ac} & t_{Ac} \\ t_c & r_c & t_{Ac} & r_{Ac} \\ r_{Ac} & t_{Ac} & r_c & t_c \\ t_{Ac} & r_{Ac} & t_c & r_c \end{bmatrix} \quad (8)$$

In Eq.8  $r_c$  stands for normal reflection of electrons or holes and  $r_{Ac}$  represents AR (reflection of an electron as a hole or vice-versa) from the barriers. Similarly,  $t_c$  represents CT or normal transmission amplitude of electrons or holes while  $t_{Ac}$  represents the nonlocal CAR amplitude for electron to hole conversion across the SDB structure. The amplitudes depend on the incident energy  $E$ , the Fermi energy  $E_F$  and the length  $L$  between the barriers.

For the normal double barrier system, resonant electron transport occurs whenever  $\theta = \pm 2q^+L = n\pi$ , which is the condition for quasi-bound states inside the double barrier. The situation for the SDB system is much more subtle. Since both electrons and holes are bounced in the normal region between the two barriers, there are multiple path dependent phases. For instance, an electron that gets reflected as an electron gets a phase of  $2q^+L$ , a hole that

gets reflected as a hole gets a phase of  $2q^-L$ , and an electron that gets Andreev reflected as a hole gets not only the path dependent phase of  $(q^+ - q^-)L$ , but also a  $\Delta$  dependent phase of  $\cos^{-1} E/\Delta$  [3].

We now obtain the resonance condition by using the technique of adding up all the Feynman paths that contribute to the transmission amplitude. However, here since we have both transmission and CAR, we need to use matrices for reflection and transmission. Let us assume the reflection and transmission matrices at each of the two superconducting barriers to be the same and given by

$$R = \begin{pmatrix} r_e & r_{Ah}\chi \\ r_{Ae}\chi & r_h \end{pmatrix} \quad \text{and} \quad T = \begin{pmatrix} t_e & t_{Ah} \\ t_{Ae} & t_h \end{pmatrix} \quad (9)$$

Note that we have allowed for the amplitudes to be electron-electron and hole-hole reflections and transmissions  $r_{e(h)}$  and  $t_{e(h)}$  to be different and also similarly electron-hole ( $r_{Ae}$  and  $t_{Ae}$ ) amplitudes to be different from hole-electron ( $r_{Ah}$  and  $t_{Ah}$ ) amplitudes. The  $\Delta$ -dependent phase  $\chi = e^{-i\cos^{-1} E/\Delta}$  [3] has also been included along with each Andreev reflection. The path-dependent phases can also be conveniently written in a matrix form as

$$P = \begin{pmatrix} \eta & 0 \\ 0 & \nu \end{pmatrix} \quad (10)$$

where  $\eta = e^{iq^+L}$  and  $\nu = e^{-iq^-L}$  are the phases picked up by the electron and hole respectively, as they move a distance  $L$ .

In terms of these matrices, if  $I_{R,L}$  and  $O_{R,L}$  (each of them are column vectors denoting electrons and holes) are the incoming and outgoing waves moving towards the left or right we find

$$\begin{pmatrix} O_L \\ O_R \end{pmatrix} = \begin{pmatrix} R + TPRQPT & TQPT \\ TQPT & R + TPRQPT \end{pmatrix} \begin{pmatrix} I_R \\ I_L \end{pmatrix} \quad (11)$$

where  $Q = (I - PRP)^{-1}$ . We define  $D = \text{Det}(I - (PR)^2)$ . The condition for resonant transport can now be easily found from the composite transmission amplitude. For an incident electron going from left to right with wavefunction given by  $I_R = (1, 0)$  ( $I_L = (0, 0)$ ), the amplitude for an electron to be transmitted towards the right (upper component of  $O_R$ ) is given by the 1-1 component of the matrix  $TQPT = TPQT$ . The explicit expression for the amplitudes are cumbersome to display, particularly since the electron-hole symmetry is broken. Similarly, the composite amplitudes for CAR (1-2 component of  $TQPT$ ), reflection (1-1 component of  $R + TPRQPT$ ) and AR (1-2 component of  $R + TPRQPT$ ) can also be found from the above matrix.

Clearly, the condition for resonant transport is now set by the vanishing of the denominator - *i.e.*, when  $D(E = E_r + iE_i) = 0$ ,  $|t_c|^2(E_r)$  has a maximum. Note that the composite amplitudes for all the 4 processes have the same denominator and hence show resonant behaviour

when the denominator goes to zero. We find that all four of them (using the correct expressions from the matrix) become  $1/4$  at resonance, which is a maximum for  $|t_c|^2$ ,  $|t_{Ac}|^2$  and  $|r_c|^2$  and a minimum for  $|r_{Ac}|^2$ . Note also that setting  $r_{A(e,h)} = t_{A(e,h)} = 0$  give the usual double barrier resonance condition, whereas setting  $r_{(e,h)} = t_{A(e,h)} = 0$  gives the resonance studied by Morpurgo and Beltram [6].

Our model does not explicitly include any external barrier at any of the normal-superconductor or superconductor-normal interfaces. In the earlier study of SDB without any barrier [6], the approximation  $\Delta/E_F \ll 1$  was also taken, which led to the vanishing of  $r$ , and consequently  $t_A$ . However, when  $\Delta/E_F$  is less than unity, but not vanishingly small (*e.g.*, we have taken  $\Delta/E_F$  between  $1/4 - 1/10$ ), back-scattering and hence a small non-zero value for  $r_i$  (which is the reflection at each barrier) does exist. We have also checked that the inclusion of normal barriers (two external  $\delta$ -function impurities at each NS interface) along with the superconducting barriers does not change the result substantially.

**Results.** – In this section we describe the consequences of all the allowed quantum mechanical processes across the SDB given by the  $\mathbb{S}$ -matrix in Eq.8.

*Resonance structure:-.* As mentioned earlier, we numerically solve the 16 linear equations obtained by matching wave-functions at the four NS junctions. We restrict ourselves to the subgap regime, where electron energy  $E$  is much less than the gap energy ( $E \ll \Delta_i$  and  $r_i$  is small). For a symmetric SDB system,  $\Delta_1 = \Delta_2 = \Delta$ ;  $\phi_1 = \phi_2$ . The behaviour of  $|r_c|^2$ ,  $|t_c|^2$ ,  $|r_{Ac}|^2$  and  $|t_{Ac}|^2$  as a function of  $E/\Delta$  is shown in Fig. 2. Note that for some particular values of  $E/\Delta$ , the coherent probabilities for all the  $\mathbb{S}$ -matrix amplitudes given in Eq.8 become  $1/4$ . Note also that the graphs show two closely spaced resonances. This can be understood from the analytic expression in Eq.11, and more specifically from the denominator  $D$ . For small values of  $r$ , there are two resonances slightly displaced from the doubly degenerate pure Andreev level resonances which occurs when  $r = 0$ . Furthermore, for  $E \ll E_F$ ,  $q^+ \simeq q^- \simeq q^F = \sqrt{2mE_F}$ , and the  $r$  term in the determinant for fixed  $E_F$  has no significant phase dependence. However, the  $r_A$  term is multiplied by the phase  $e^{i(q^+ - q^-)L}$ . Hence, we have plotted the variation of the transmission and CAR probabilities as a function of  $\theta = (q^+ - q^-)L$ , in Fig.3(a). Note the approximate periodicity of the resonances is for  $\theta \rightarrow \theta + 2\pi$ .

The width of the resonance depends on the back-scattering that occurs at a single barrier, which in turn, depends on the value of  $\Delta/E_F$  (for  $r_{Ai}$ ) and the scattering potential at the barrier (for  $r_i$ ). We have checked numerically that changing  $\Delta/E_F$  between  $1/4 - 1/10$  changes  $r_{Ai}$  which affects the width of the resonances, and changing the strength of the  $\delta$ -function impurities changes  $r_i$ , but otherwise has very little affect on the character of the graph. Hence, we have presented our results only for  $\Delta/E_F = 0.275$  and  $\lambda = 0$ , where  $\lambda$  is the strength of the

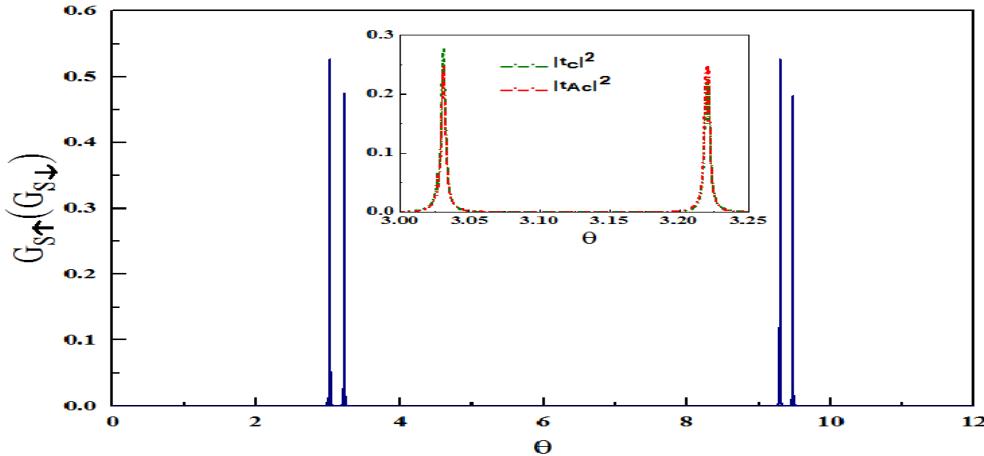


Fig. 3: The behaviour of the spin conductance  $\propto |t_c|^2 + |t_{Ac}|^2$  for spin  $\uparrow$  ( $\downarrow$ ) polarised electrons, is shown, in units of the incident spin, as a function of  $\theta = (q^+ - q^-)L$  for a symmetric SDB system. The parameter values are given by  $E/\Delta = 0.078$ ,  $\Delta/E_F = 0.275$  and  $\phi_1 = \phi_2 = 0.4\pi$ . The inset shows the variation of  $|t_c|^2$  and  $|t_{Ac}|^2$  close to the resonance, in units of  $e^2/h$ . Note the closely spaced resonances in the inset.

$\delta$ -function.

Setting  $r_i = 0$  exactly reverts to the problem studied by Morpurgo and Beltram [6] which has only a  $T = 1$  resonance. This is similar to the usual  $|t|^2 = 1$  resonance of a standard normal DB system, (which is obtained by setting  $r_{Ai} = 0$ ) although the physical origin is different, since for the SDB structure, the electron gets Andreev reflected at each bounce between the barriers, instead of getting normally reflected. As long as the multiple bounces between the barriers occur either through normal reflection or Andreev reflection, but not both, the transmission resonance remains unimodular. On the other hand in our case, we have allowed for all the quantum mechanical processes that can occur at each barrier. Hence, we have multiple bounces between the two barriers involving both  $r_i$  and  $r_{Ai}$ . This seems to lead to a new non-unimodular resonance at  $T = 1/4$ , where in fact, all the quantum mechanical probabilities become  $1/4$  because all the 4 processes show resonant behaviour. *This is the main point of this letter.* It is hence clear that the very occurrence of the  $T = 1/4$  resonance requires the presence of all the four amplitudes *i.e.*, in a ‘single’ channel problem with just one reflection and one transmission, the only resonance that is possible is the standard unimodular resonance. The non unimodular  $T = 1/4$  resonance requires the presence of two ‘channels’.

*Pure spin current:-.* As an application of the above SDB geometry, we point out that this geometry can be used to produce pure SC in a resonant fashion. The proposal for generating pure spin current using NSN junction was discussed earlier in Ref. [15], but there it involved non resonant production of pure SC unlike the present case. In our analysis the *spin conductance* is de-

fined as  $G_{S\uparrow}(G_{S\downarrow}) \propto |t_{Ac}|^2 + |t_c|^2$  in units of the incident spin, whereas the *charge conductance* is given by  $G_{C\uparrow}(G_{C\downarrow}) = (e^2/h)[|t_{Ac}|^2 - |t_c|^2]$ . The  $\uparrow$  and  $\downarrow$  arrows in the subscript represent the spin polarization of the injected electrons from the ferromagnetic reservoir as shown in Fig.1. The sum of contributions coming from two oppositely charged particles (electrons and holes) gives rise to the negative sign in the expression for  $G_{C\uparrow}(G_{C\downarrow})$ . The interesting point to note here is that for an electron incident on the barriers, if the amplitudes for the CT and CAR are identical, then it will result in equal probability for an incident electron to transmit as an electron or as a hole across the barriers. This results in the vanishing of the charge current. On the other hand, in our geometry, if the incident electron in the lead is  $\uparrow$  or  $\downarrow$  spin polarized, then both the transmitted electron due to  $t_c$  and hole due to  $t_{Ac}$  will have the same spin polarization. This is true because in our analysis we have assumed that the superconducting patches are spin singlets and hence spin remains conserved. Note, however, that if the incident electrons were not spin polarised (*i.e.*, if we had a normal metal reservoir instead of a ferromagnet), then even when CT and CAR are equal, there would be both up and down spin electrons and holes transmitted, and hence there would be no SC. Therefore, when the symmetric SDB structure with a ferromagnetic reservoir is tuned to resonance *i.e.*  $|t_c|^2 = |t_{Ac}|^2 = \frac{1}{4}$  and if a spin polarized beam (say  $\uparrow$  spin polarized according to Fig.1) of electrons is incident on the barriers, then the outcome would be resonant production of outgoing pure SC. In this resonant situation 25% of the incident spin-up electrons get transmitted through the barriers via the CT process and 25% get converted to spin-up holes via the CAR process as they

pass through the barriers. Hence the transmitted charge across the barriers is zero on the average, but there is pure SC flowing out of the system. The behaviour of  $G_{S\uparrow}(G_{S\downarrow})$  for the SDB system as a function of  $(q^+ - q^-)L$  is shown in Fig.3(b). At the resonance,  $G_{S\uparrow}(G_{S\downarrow})$  becomes 0.5 and  $G_{C\uparrow}(G_{C\downarrow})$  becomes 0 for a spin polarized electron beam which is a clear manifestation of pure SC in a SDB geometry.

**Discussions and Conclusions.** — In this letter, we have studied a superconducting double barrier system and have shown that one can tune a  $T = 1/4$  resonance in the system. It is crucial to have non-zero amplitudes for all the four amplitudes, reflection, Andreev reflection, normal transmission and crossed Andreev reflection to see this resonance. Note also that we have restricted ourselves to the Blonder-Tinkham-Klapwijk approximation [1] of neglecting the single electron transfer across the barrier. Hence, we have shown the resonance only in the thick barrier limit, where the transparency is low. A similar resonance was already noted by some of us [24] in a stub geometry where all these four amplitudes were non-zero. The special value of  $T = 1/4$  was also noted earlier by some of us [10, 15] in the context of a weak interaction renormalisation group study of a NSN junction, where a non-trivial fixed point was found which had  $T = 1/4$ . In all these contexts, not only does  $T$  have a non-unimodular value, all the other amplitudes also have a value of  $1/4$ , ( $|t_{Ac}|^2 = |r_c|^2 = |r_{Ac}|^2 = 1/4$ ) as required by unitarity. In all these contexts, pure SC is the outcome (at resonance or at the fixed point), since the charge current gets nullified on the average.

As far as the practical realization of such a SDB structure is concerned, it should be possible to fabricate such a geometry by depositing thin strips of a spin singlet superconductor (like  $Nb$  with  $\Delta \sim 1.5$ meV [11]) on top of a ballistic quantum wire (with  $E_F \sim 1$ eV [25]) or a carbon nanotube at two places. The width of the strips should be of the order of the superconducting phase coherence length ( $10 - 15$ nm in case of  $Nb$ ). The  $T = 1/4$  resonance in this SDB geometry can be tuned by varying the energy of the incident electron (which can be done by applying a small bias voltage between the two reservoirs keeping within linear response, so that our calculations are valid) for fixed distance ( $\sim 0.5\mu m$ ) between the two barriers or the distance between the two barriers for fixed incident energy. However, inclusion of electron-electron interaction, finite temperature, finite bias, etc can lead to very interesting physics in the presence of resonances which is beyond the scope of the present work.

In conclusion, in this letter we have studied resonant transport through a SDB structure where, at an energy scale much below the superconducting gap  $\Delta$ , probabilities for all the coherent amplitudes become  $1/4$  in the tunneling (or thick barrier) approximation. As an application we have also discussed the possibility for production of resonant pure SC in this structure.

**Acknowledgements.** — We thank Sourin Das for many stimulating and useful discussions and also a careful reading of the manuscript. We acknowledge use of the Bewoulf cluster at HRI for our numerical computations.

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